AMMO:
An Automated Multiple Maneuver Optimization System

Christopher L. Potts†, John R. Michel‡,
and Behzad Raofi†*

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

An automated maneuver design capability can provide significant benefits in cost, risk reduction, and science return for interplanetary spacecraft missions. Emphasis must be placed on a general and robust approach to accommodate the diversity of complex missions, both present and future. Maneuver optimization provides a highly desired sophisticated Δv solution, but also increases complexity and introduces significant automation challenges. An Automated Multiple Maneuver Optimization (AMMO) system is presented in this context. Additionally, the prototype system has proven to be extremely successful with *Stardust* operations support.

† Member of Engineering Staff, Navigation and Mission Design Section
‡ Professor of Mathematics, Marietta College, Marietta, Ohio, and JPL Consultant
* Member AAS

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Introduction

Interplanetary spacecraft missions have evolved from relatively quick hyperbolic reconnaissance to a desire for extended orbital presence, in situ measurements, and sample return capability. To achieve the enhanced mission objectives, mission plans require an increasing number of trajectory correction maneuvers and potentially frequent gravity assist encounters during orbital tours. Consequently, the flight path control challenges encountered with current and future interplanetary spacecraft missions continue to advance in complexity and risk.

While the missions are more challenging than ever, the desire always exists to improve efficiency and thereby reduce operation costs. Automating frequently performed tasks in a robust manner is a proficient way to achieve these goals. Executed properly, automation can help achieve many of the time-critical mission requirements while enabling a reduction in both mission risk and operation costs.

Lowering the cost of interplanetary spacecraft exploration requires the development of capable automation tools. This paper outlines an automated multiple maneuver optimization system designed to routinely determine the optimal Δv requirements from updated orbit determination solutions while satisfying the mission specific constraints. This system has demonstrated its effectiveness through prototype use on operational missions and analysis of upcoming missions.

Optimization

Maneuver optimization has become a prevalent analysis tool to significantly reduce mission propellant requirements. By re-optimizing the trajectory during operations, control variables are adjusted to minimize the cost of correcting spacecraft state variations that occur within the realm of

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orbit determination uncertainties. The optimization process is also utilized to maintain control of the variables that define the trajectory requirements of the mission. In the maneuver design process, the optimization step represents a sophisticated general solution to Δv determination. The result is savings in propellant, improved margins in consumable resources, and reduced mission cost.

A significant detriment to using optimization is that the algorithms often require close monitoring and user interaction to achieve an acceptable solution. Frequently, existing algorithms suffer convergence problems in the search for the absolute optimal solution or are ill suited for the specific maneuver optimization application at hand. New algorithms are making progress in terms of reliability and capability, but this improvement comes with an increase in complexity for the general user. Optimization algorithms are generally not conceived for use in an automated approach.

The maneuver optimization problem associated with spacecraft flight operations contains inherent advantages to utilize in the quest for an automated capability. The most significant advantage is the ability to start with a very good initial estimate of the optimal solution. Prior to flight operations, the mission design process defines the optimal reference trajectory. This nominal trajectory provides the initial estimates of the key control variables that define the reference mission. The task is to re-optimize the trajectory after incorporating new estimates of the initial spacecraft state and model variations. The spacecraft state and model updates result from the processing of navigation tracking data acquired in flight. With each optimization cycle, a new reference trajectory is created which provides initial control state estimates for use in the subsequent optimization. In this manner a good initial state estimate, which is generally critical for a reliable optimization solution, is routinely available during spacecraft operations.

A second flight operation advantage to utilize in an automated optimization algorithm is the recognition of system uncertainties and appropriate control thresholds. Frequently, existing algorithms suffer convergence problems in the search for the absolute optimal solution. In flight operations the emphasis is directed toward an acceptable solution that satisfies the critical mission constraints. An acceptable solution is one that is optimized to the level of the system control capability and not necessarily the absolute numerical optimum. The acknowledgement of system control thresholds is utilized to simplify the optimization problem by removing control variables from the problem definition. As a result, an acceptable solution can be obtained before the optimization algorithm encounters a potential numerical instability.

AMMO System

The AMMO system consists of prototype software with the necessary core capabilities to minimize the total mission Δv from a series of impulsive maneuvers, subject to trajectory and maneuver constraints. The key to the AMMO objective is the ability to automatically converge on an optimal trajectory solution. The system architecture, which defines the optimization problem, is identical to the trajectory structure described in Reference [1]. Although non-linear and genetic optimization algorithms were considered, a linear re-weighted least-squares optimization approach was selected based on its relative simplicity and reliability. Numerous algorithms and tools are applied to provide the proper feedback control in the successive linear solutions to the original highly nonlinear problem. In this manner, convergence is robustly achieved without requiring any user interaction.

The software system currently consists of generalized Matlab code developed in a test bed environment. Existing algorithms and executables from Navigation and Mission Design software at JPL are utilized as much as possible to expedite the analysis. This environment provides the tools to investigate different automation approaches and determine their relative merits. The optimization results are based upon relatively high precision system models, albeit less sophisticated in some respects from the modeling normally used in navigation operations. Consequently, the AMMO system currently provides the optimized targets for operational use. The optimized Δv results from AMMO show very good agreement with the operational software by paying close attention to the modeling details between the two environments.

In the longer term, the algorithms developed will be available for infusion in the next generation of navigation software to provide an automated optimization capability for spacecraft ground operations. For more immediate use, the AMMO system has been integrated to work with the existing navigation operational software. In this context the prototype system has proven to be extremely successful for Stardust operations support.

The system can be run as a software engine, making the maneuver optimization entirely automated in a black box type fashion. The trajectory state and model updates are sent via email to the AMMO system engine, which automatically sets the re-optimization process in motion. The AMMO system uses this delivered information to define the optimization problem and determine the optimal target parameters and minimized Δv. The optimized targets from AMMO are utilized in the navigation operation software to determine a high precision reference trajectory and obtain an optimal Δv solution. The AMMO system reduces a user involved process that can take between 8-10 hours including setup time, to a purely automated process requiring approximately 15 minutes.

References

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